NASA Space Radiation Summer School
June 3 - 26, 2015
Brookhaven National Laboratory
Upton, New York

SPACE RADIATION

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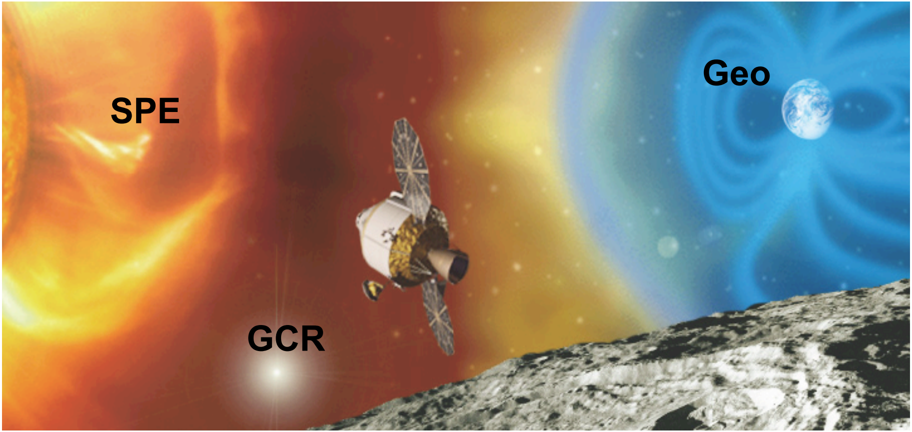
Tuesday June 9, 2015

OUTLINE

3 SOURCES OF SPACE RADIATION

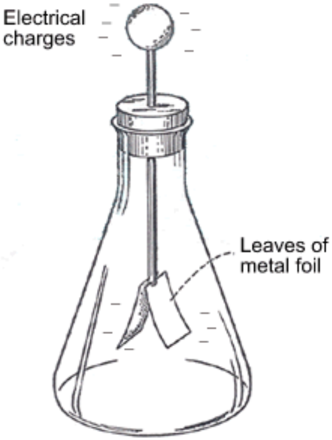


[https://oltaris.larc.nasa.gov]

Galactic Cosmic Rays (GCR) - Discovery

- It all began with a mystery surrounding the continuous & uncontrollable leakage of electrical charge from a well insulated charged gold leaf electroscope.

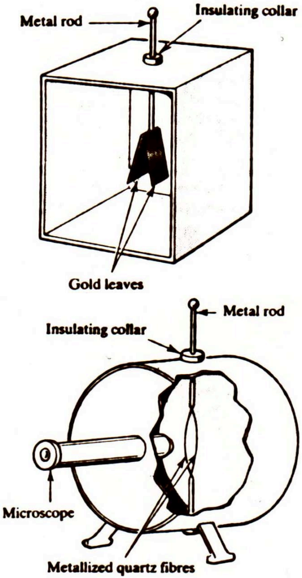
- Mystery unexplained since Henry Coulomb noticed in 1785, that charged metal sphere suspended by insulated silk thread did not retain charge.



[http://www.school-for-champions.com/experiments/]

Galactic Cosmic Rays (GCR) - Discovery

- In early days electroscopes & electrometers also used to study x-rays, radioactivity, etc.
- X-rays & radioactive emanations ionize gases
- Strong sources of radiation cause leaves in electroscope to come together
  (after electroscope initially charged)
- Strength of radiation can be measured by how quickly leaves come together

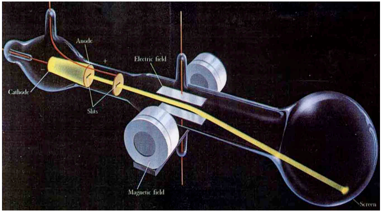


[Close et al., The particle explosion, Oxford Univ. Press, Oxford, 1994]

GALACTIC COSMIC RAYS (GCR) - DISCOVERY

Researchers found trouble:

- Turn of all Crookes tubes, remove all radiation sources, remove light
- Still electroscope leaves fall together



[Lederman & Schramm, From quarks to the cosmos, Freeman, New York, 1989]

End of C19 Wilson connected this to ionization of surrounding air

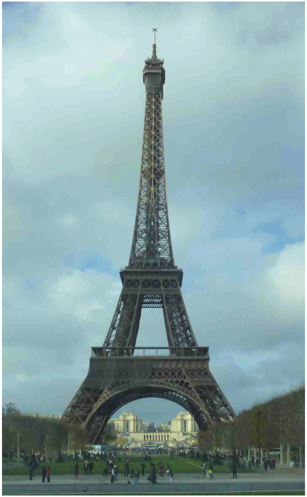
- With discovery of radioactivity & finding that earth itself contained minute traces of radioactive materials, it was mistakenly thought that source of ionization of air was this radioactive material of earth.

GALACTIC COSMIC RAYS (GCR) - DISCOVERY

Implied that leakage rate (rate at which leaves come together) should be smaller at higher altitudes

1910 Father Thomas Wulf took electroscope to top of Eiffel tower

- Observed 64% drop in leakage rate
- But expected much more reduction (radiation should be absorbed in air)
- Deduced that radiation from ground (gradually decreasing with height) competing with radiation coming down through atmosphere
- Obvious thing was to go to greater heights (Wulf did not!)



[Norbury, 2010]

Galactic Cosmic Rays (GCR) - Discovery

Starting in 1911, Victor Hess (Austrian) was first to produce decisive results from balloon flights in which he ascended with electroscopes

- Radiation first decreased as balloons went up
- But by 5,000 ft. radiation was more intense than at sea level
- By 17,500 ft. radiation increased several times
- Hess hypothesized "extra-terrestrial source of radiation"
- Named *Cosmic Radiation* by Millikan in 1925

[Friedlander, Nature 483, 400, 2012]

GCR Composition, Spectrum, Origin

3 regions

- High Energy $<$ PeV
- Very High Energy (knee) PeV - EeV
- Ultra High Energy (ankle) $>$ EeV

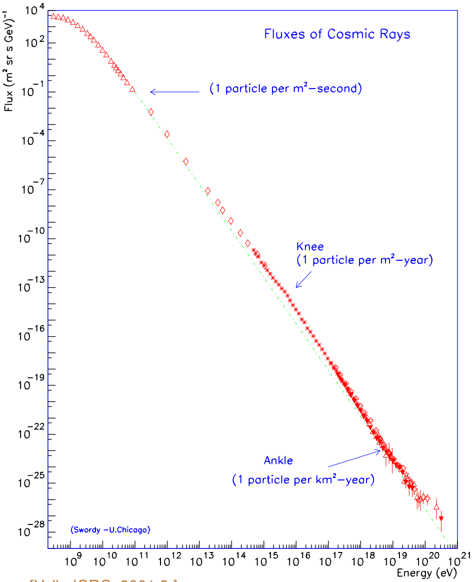
keV = 10^3eV MeV = 10^6eV
GeV = 10^9eV TeV = 10^{12}eV
PeV = 10^{15}eV EeV = 10^{18}eV
ZeV = 10^{21}eV

Tevatron collider

2 TeV cm $\Rightarrow$ 10 PeV lab

Large Hadron Collider

14 TeV cm $\Rightarrow$ 400 PeV lab



[Volk, ICRC, 2001:3]

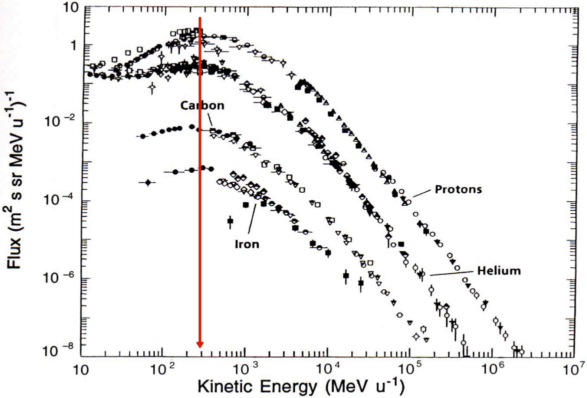
Space radiation problem

GCR (primary) composition

- 98% nuclei, 2% $e^+ e^-$
- Nuclear component:
  87% Hydrogen
  12% Helium
  1% heavy nuclei

GCR origin

- Emitted in stellar wind & flares & accelerated by supernova shock waves (within our Galaxy)

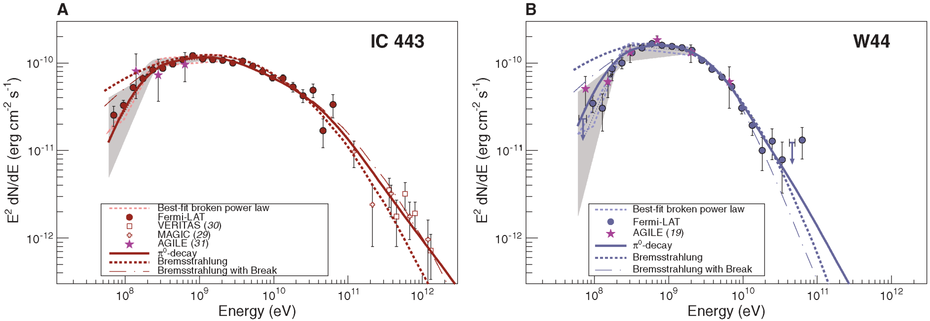


[Simpson, Ann. Rev. Nucl. Part. Sci. 33, 323, 1983]

GCR High Energy < PeV

Supernova proof - Fermi γ telescope 2013

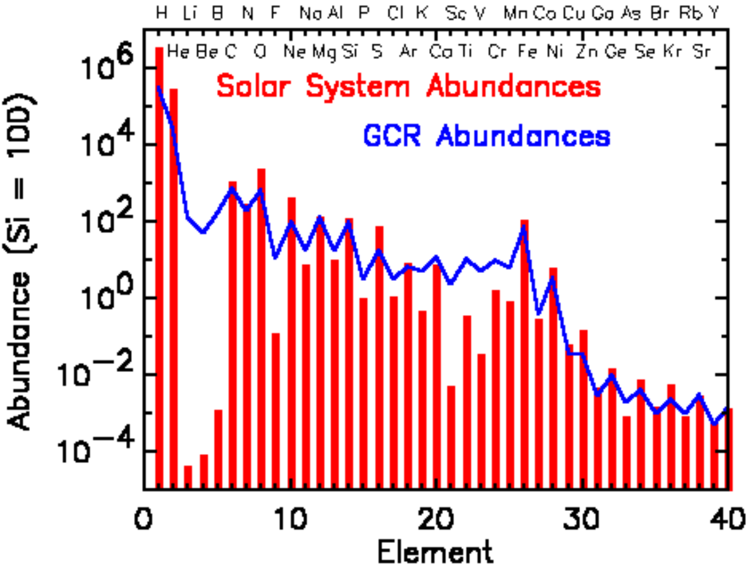
- Lower energy fits π^0 spectrum (not bremsstrahlung)



(**A** and **B**) Gamma-ray spectra of IC 443 (A) and W44 (B) as measured with the Fermi LAT. Color-shaded areas bound by dashed lines denote the best-fit broadband smooth broken power law (60 MeV to 2 GeV); gray-shaded bands show systematic errors below 2 GeV due mainly to imperfect modeling of the galactic diffuse emission. At the high-energy end, TeV spectral data points for IC 443 from MAGIC (*29*) and VERITAS (*30*) are shown. Solid lines denote the best-fit pion-decay gamma-ray spectra, dashed lines denote the best-fit bremsstrahlung spectra, and dash-dotted lines denote the best-fit bremsstrahlung spectra when including an ad hoc low-energy break at 300 MeV c^{-1} in the electron spectrum. These fits were done to the Fermi LAT data alone (not taking the TeV data points into account). Magenta stars denote measurements from the AGILE satellite for these two SNRs, taken from (*31*) and (*19*), respectively.

[Ackermann et al., Science 339, 807, 2013]

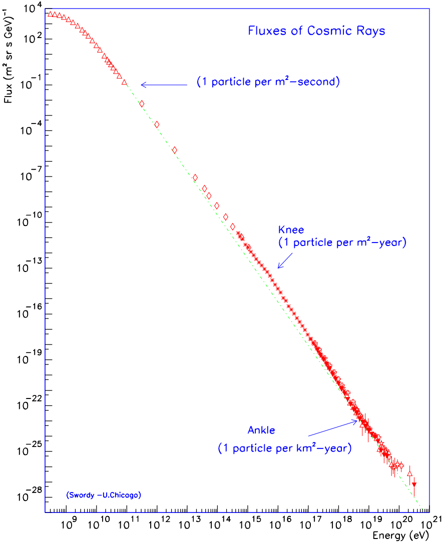
GCR High Energy < PeV



[http://imagine.gsfc.nasa.gov/Images/science/abund2.gif]

Possible models for Knee

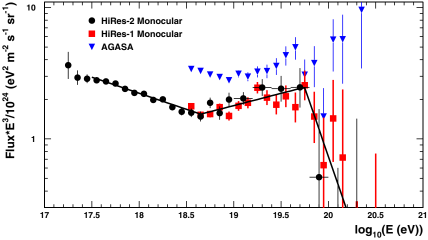
- Increasing loss because $B_{\mathrm{ISM}} \sim 3\mu\mathrm{G}$ can no longer contain high energy particles ... and/or
- Sources of cosmic rays (i.e. supernovae) have a max energy cutoff
- Wolfendale - Single supernova (Galactic) source i.e. another cosmic ray component pokes through a smoothly falling background spectrum



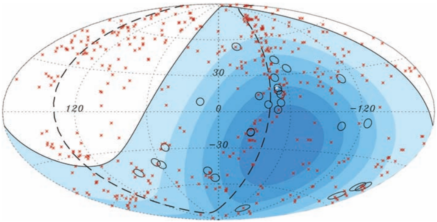
[Volk, ICRC, 2001:3]

ULTRA HIGH ENERGY (ANKLE) > EEV (EGCR)

- 1965 CMBR (Penzias & Wilson)
- 1966 Greisen, Zatsepin, Kuzmin (GZK) predicted 10^{20}eV cutoff
- Observed 2008 (HiRES Flye's Eye)
- Angular isotropy (AGN) (Auger) $E > 6 \times 10^{19}$eV
- Beginning of cosmic ray astronomy



[Abbasi et al., Phys. Rev. Lett. 100, 101101, 2008]



[Abraham et al., Science 318, 938, 2007]

GCR - ANTIMATTER (e^+, p^-)

Universe

- Ordinary Matter 5%
- Dark Matter (DM) 20%
  - Most viable particle = Neutralino

  = Lightest Supersymmetric Particle (LSP) = Weakly Interacting Massive Particle (WIMP)
- Dark Energy 75%

e^+, p^- prime targets for indirect detection of Galactic DM

Possible sources of e^+, p^-

- Primary Production:
  - Annihilation of DM particles
  - Evaporation of Primordial black holes
  - Kaluza-Klein particles (=WIMP)
  - Pulsar, Supernova remnant, Microquasar
- Secondary production:
  - *pp* collisions (GCR with protons in Interstellar medium)

GCR - Antimatter (e^+, p^-)

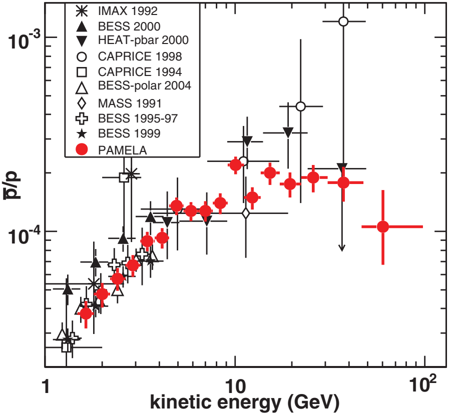
PAMELA (satellite)

- Payload for AntiMatter Exploration & Light nuclei Astrophysics
- p^- consistent with secondary production
- Excess of e^+ (1 - 100 GeV) (DM?)

ATIC (balloon Antarctica)

(Wefel, Adams)

- Advanced Thin Ionization Chamber
- Excess of e^{+-} (300 - 700 GeV)
  e^{+-}="electrons"
  (can't distinguish charge)



Antiproton to proton flux

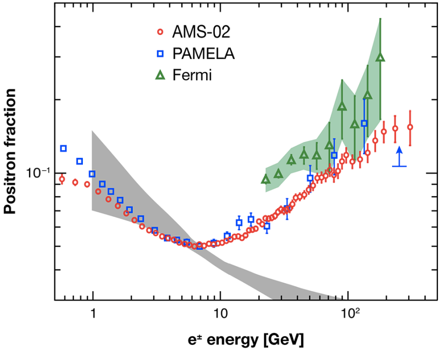
[Adriani et al., Phys. Rev. Lett. 102, 051101, 2009]

GCR - ANTIMATTER (e^+, p^-)

AMS confirms positron excess

- "Disagreement" at low energy simply different geomag cutoff (disappears at high energy)
- Grey band: pp $\rightarrow \pi \rightarrow e^+$ in galaxy

[http://ams.nasa.gov]

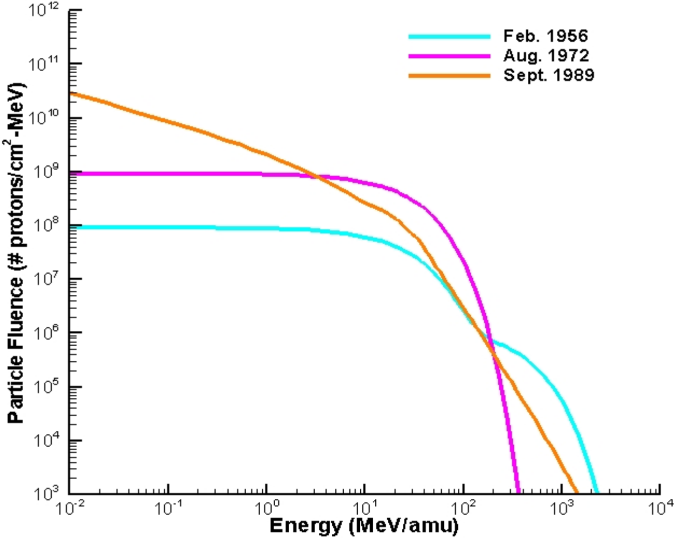


The positron fraction in high-energy cosmic rays. The new measurement from the AMS extends over a wider energy range and has much lower uncertainty than the earlier measurements from the PAMELA and Fermi-LAT satellites (or older balloon experiments). The AMS measurement confirms an excess in the high-energy positron fraction, above what is expected from positrons produced in cosmic-ray interactions.

The grey band indicates the expected range in the positron fraction.

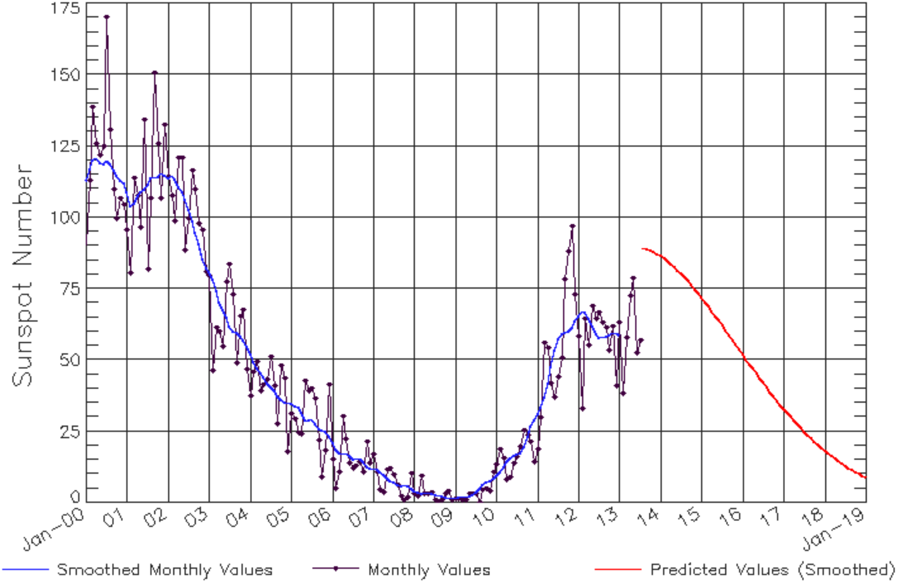
[Aguilar et al., Phys. Rev. Lett. 110, 141102, 2013]

e, p & some heavy nuclei < 1 GeV/N (v $\sim$ 0.9c)



SPE Proton spectra [Clowdsley et al., AIAA, 2006]

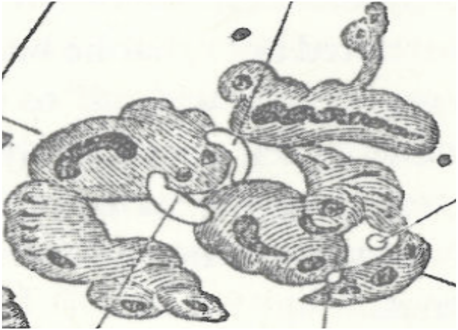
SOLAR PARTICLES 11 YEAR CYCLE - 2014 NEAR MAXIMUM!



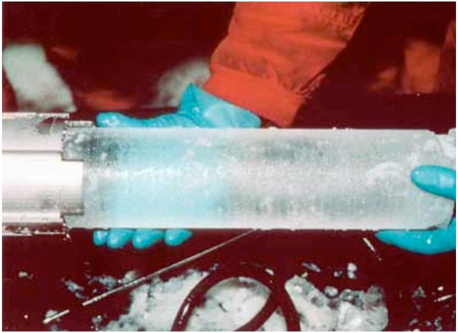
[NOAA, 2013]

Solar particles - Carrington Event 1859

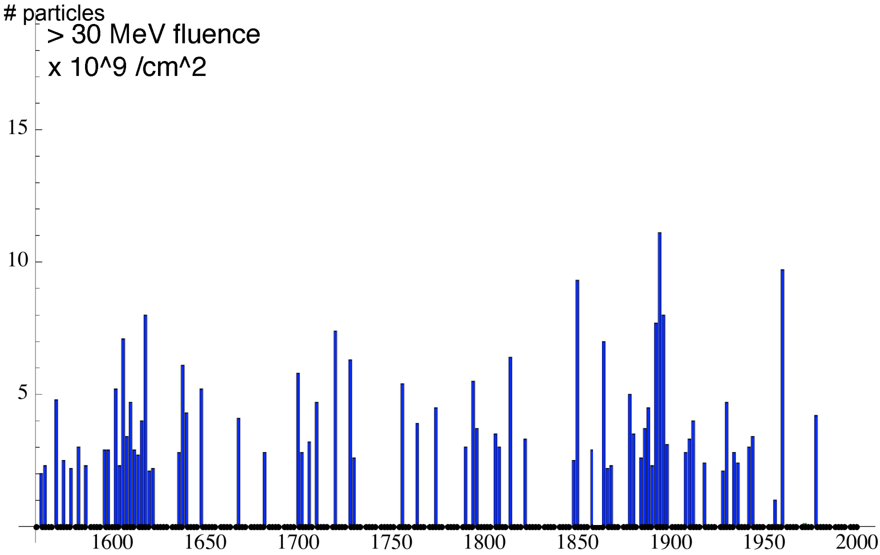
- Carrington event 1859
- Energetic solar protons create nitrates & ^{10}Be in upper atmosphere
- Settle into Greenland ice cores



[Clark, The sun kings, Princeton, 2007]

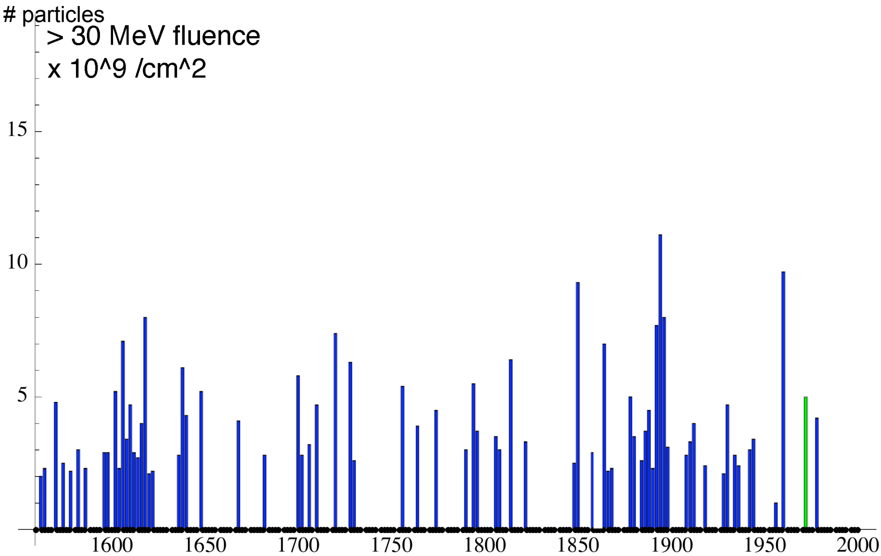


[Kennedy, Science 311, 1673, 2006]

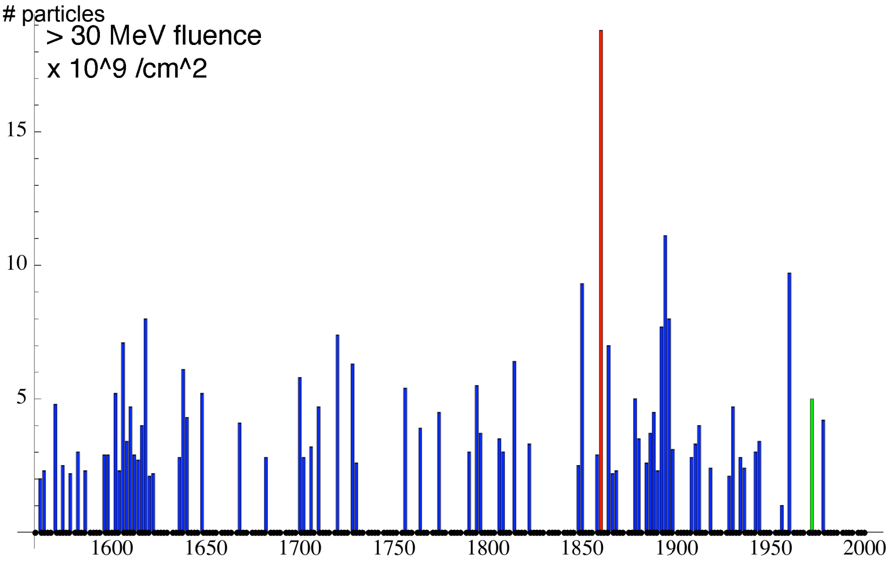


particles
> 30 MeV fluence
x 10^9 /cm^2
15
10
5
1600
1650
1700
1750
1800
1850
1900
1950
2000

SOLAR PARTICLES - CARRINGTON EVENT 1859



SOLAR PARTICLES - CARRINGTON EVENT 1859



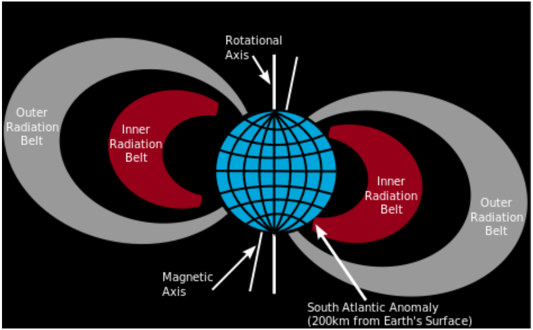
GEOMAGNETICALLY TRAPPED PARTICLES

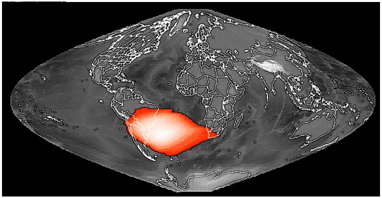
Inner belt: 0 - 3 R_E = 18,000 km - mainly p

- Starts about 3,000 km
- But SAA dips down to 400 km

Outer belt: 3 - 12 R_E = 36,000 km (e,p) - mainly e

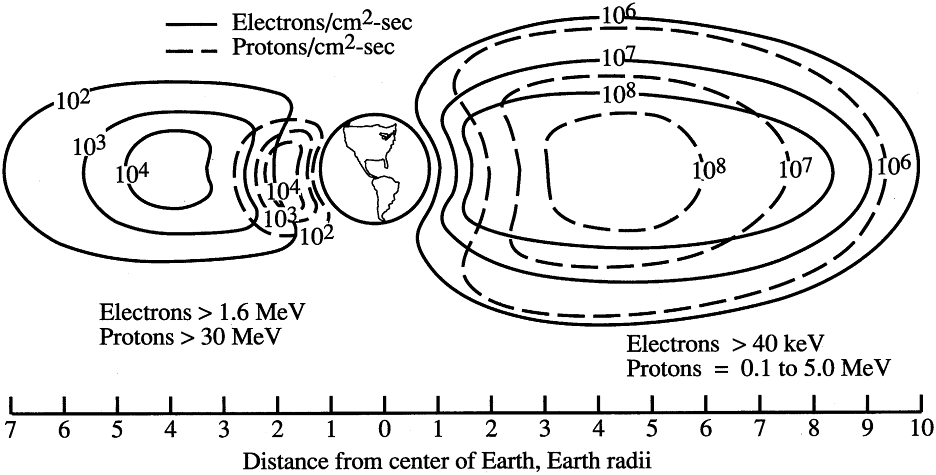
(LEO: 200 - 500 km GEO: 22,000 miles = 35,000 km)





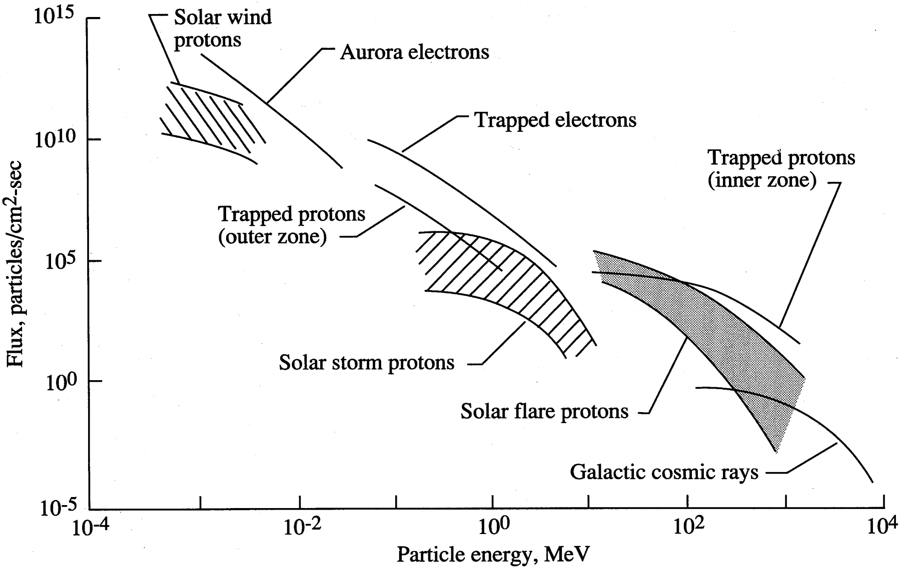
[Wikipedia, 2014] [http://science1.nasa.gov/science-news/science-at-nasa/2001]

GEOMAGNETICALLY TRAPPED PARTICLES



[Wilson et al., NASA-RP 1257, 1991]

GEOMAGNETICALLY TRAPPED PARTICLES

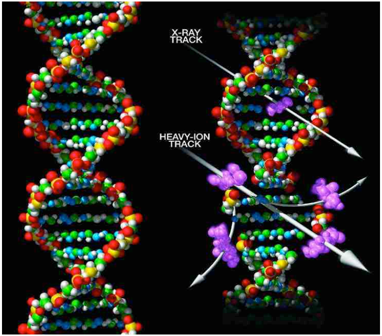


[Wilson et al., NASA-RP 1257, 1991]

RADIATION & DOSE

Unit of absorbed dose:
1 Gray == 1 J/kg

Radiation quality factor Q
Sievert = Gray $\times Q$



[http://www.nasa.gov/centers/marshall/multimedia/photos/2003/photos03-183.html]

ICRP estimate: 5% per Gy
1 in 20,000 risk of fatal cancer per 1 mSv dose (lifetime)

RADIATION & DOSE

Cross Sections σ_i , σ_{ij} PHYSICS (NUCFRG, QMSFRG)

Boltzmann TRANSPORT Eqn $\Rightarrow$ FLUENCE ϕ_i $[\#/cm^2/MeV]$ (HZETRN)

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S_i(E) + \sigma_i(E)\right] \phi_i(x, E) = \sum_j \int_E^\infty dE' \, \sigma_{ij}(E, E') \, \phi_j(x, E')$$

$$\text{Dose} \quad D(x) = \sum_i \int_0^\infty dE \, S_i(E) \, \phi_i(x, E) \qquad [\mathrm{Gy} = \mathrm{J/kg}]$$

$$\text{Dose Equivalent} \quad H(x) = \sum_i \int_0^\infty dE \, Q(L_i(E)) \, L_i(E) \, \phi_i(x, E) \qquad [\mathrm{Sv}]$$

$$\text{Effective Dose} \quad E = \sum_T w_T \, H_T \qquad [\mathrm{Sv}] \qquad \Rightarrow \text{Risk}$$

BIOLOGY $Q(L_i), w_T$

$$L_i \equiv \frac{dE}{dx} \approx S_i(E)$$

Dose Equivalents

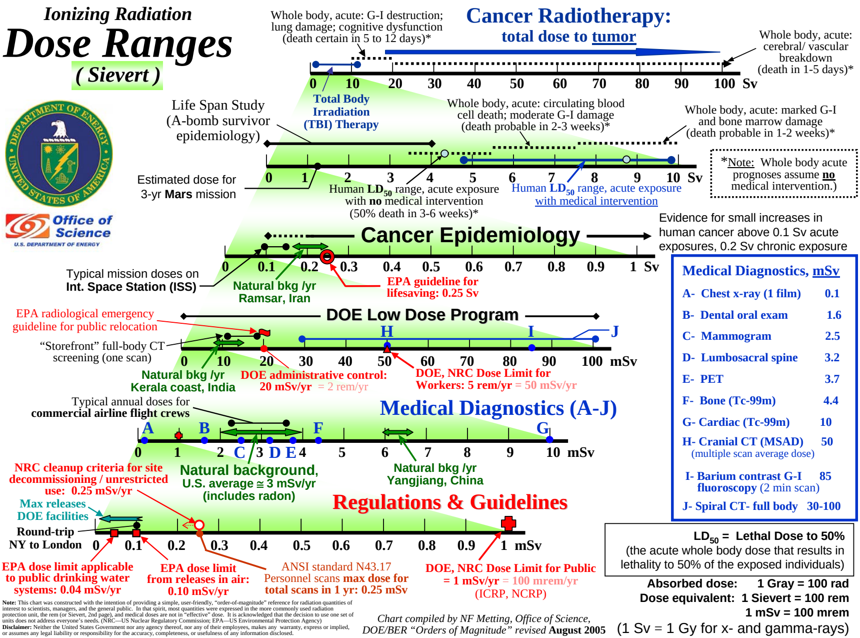
	Dose Equivalent (mSv)
Chest x-ray	0.1
USA annual background	4
Public annual limit (above background)	1
International Airline crews	4
Radiation worker annual limit	20
No observed effects (Abomb)(instant)	200
Blood count changes	$>$200
Acute Radiation Syndrome (ASR)	1,000
Death (instantaneous dose)	3,000
Mir, ISS (with shield) annual	150
Large solar flare (free space)	10,000

ICRP cancer risk estimate: 5% per Gy $\sim$ 5% per Sv (for Q=1)

1 in 20,000 risk of fatal cancer per 1mSv dose (lifetime)

DOSE EQUIVALENTS 500 mSv - 1 Sv

- A bomb instant (0 - 4 Sv)
- Astronaut limit
- NSRL 1 minute (1 - 25 Gy/min depending on beam)
- SPE 1 hour
- GCR 1 year



[USA Department of Energy]

Dose Equivalents

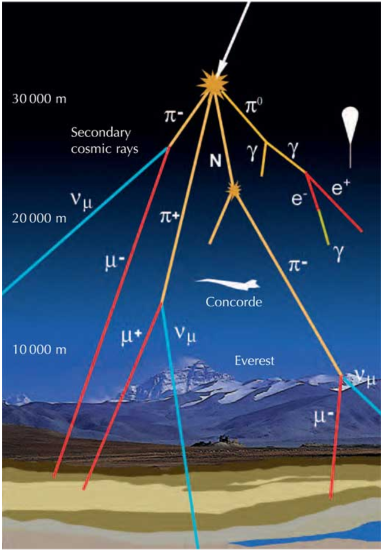
Age- and gender-dependent career effective dose limits (in Sv) as recommended by different space agencies (Cucinotta, Hu *et al.*, 2010; Straube *et al.*, 2010). NASA limits are always based on 3% risk of exposure-induced death, and the values refer to a 1 yr mission. Different values will be calculated for different mission durations (Cucinotta, Hu *et al.*, 2010).

		Age at first exposure, (yr)			
Space agency	Gender	30	35	45	55
NASA (USA)	Female	0.47	0.55	0.75	1.1
	Male	0.62	0.72	0.95	1.5
JAXA (Japan)	Female	0.6	0.8	0.9	1.1
	Male	0.6	0.9	1.0	1.2
ESA		1.0	1.0	1.0	1.0
FSA (Russia)		1.0	1.0	1.0	1.0
CSA (Canada)		1.0	1.0	1.0	1.0

[Durante & Cucinotta, Rev. Mod. Phys. 83, 1245, 2011]

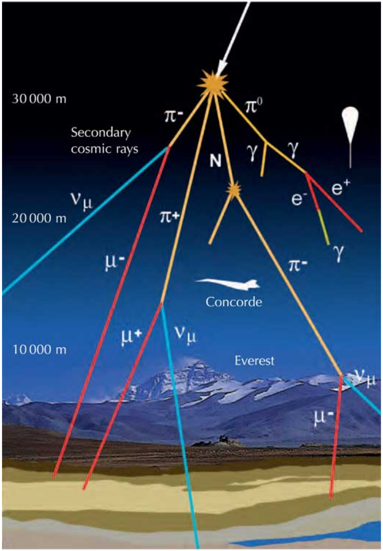
AIRCRAFT

AIRCRAFT



[http://www.scienceinschool.org/2010/issue14/cloud/maltese]

AIRCRAFT



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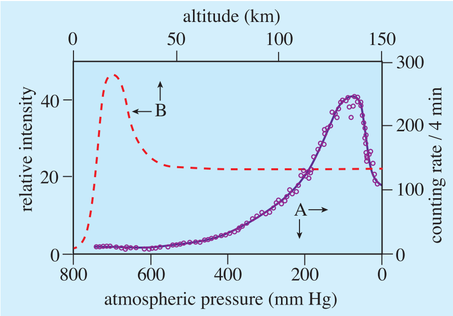


[Bancroft et al., Phys. Ed. 49, 164, 2014]

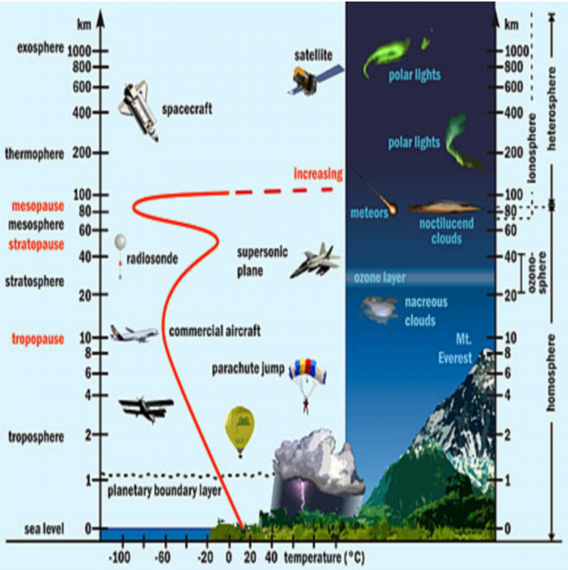
AIRCRAFT

- Domestic crews 1 - 2 mSv /yr
- International crews $<$ 4 mSv / yr
- Pregnant woman $<$ 5 mSv
  (to fetus per pregnancy)

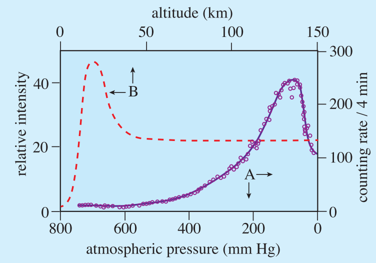
Aircraft - Why all the concern now?

- NCRP & ICRP have lowered radiation worker exposure
  - 50 mSv / yr to 20 mSv / yr
- Air crews most highly exposed of any occupation group
- FAA criticized for not paying enough attention
- Many more polar flights
- Future High Speed Civil Transport (HSCT) radiation levels
  - 3 times higher than for crews of subsonic transport
- Only solution available now:
  - reduce flight hours
- NAIRAS - Mertens (Langley)

AIRCRAFT - HIGH SPEED CIVIL TRANSPORT (HSCT)



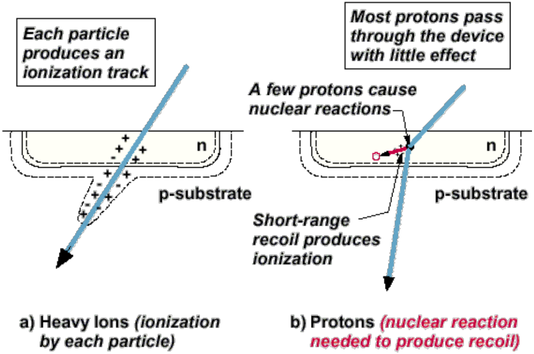
[http://www.ubthenews.com/topics/ionosphere.htm]



[Bancroft et al., Phys. Ed. 49, 164, 2014]

Computers

- Junction density increasing
- Switching energy decreasing



[http://holbert.faculty.asu.edu/eee560/see.html]

Need for predicting Single Event Upsets (SEU)

- satellite electronics
- aircraft electronics (civilian & military)

Shuttle - several hundred SEU / mission

Electronics - Deep Space

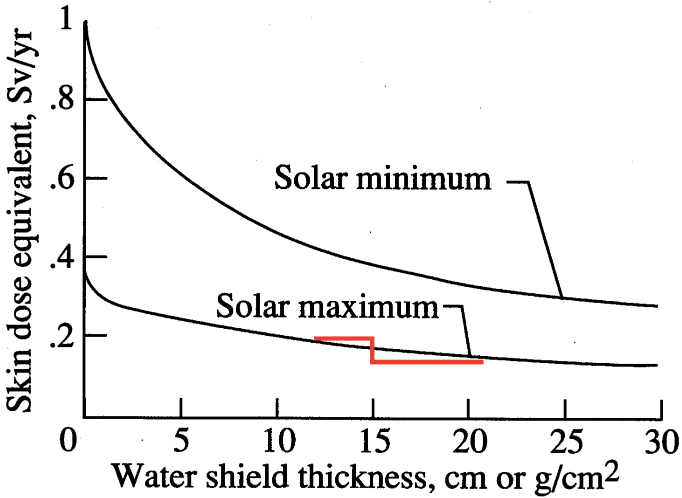
- Electronics on Spirit, Opportunity, Curiosity etc. are radiation hardened
- Shielding very important for Jupiter, Saturn

[http://mars.jpl.nasa.gov/msl/multimedia/images/?imageid=3504]

[Credit: NASA/JPL/Space Science Institute]

[http://photojournal.jpl.nasa.gov/catalog/PIA04866]

Features of Galactic Cosmic Radiation



Dose equivalent as a function of water shield thickness from GCR

[Wilson et al., NASA-RP 1257, 1991]

NUCLEAR & PARTICLE PHYSICS & TRANSPORT

These are the doses received

- How were results obtained?
- How to design spacecraft & aircraft shields so dose is minimal?

Need

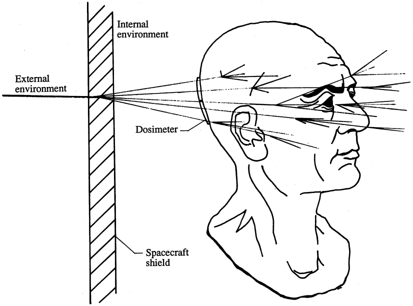
- Accurate atomic, nuclear, particle physics theory
- Accurate transport theory
- Biological models

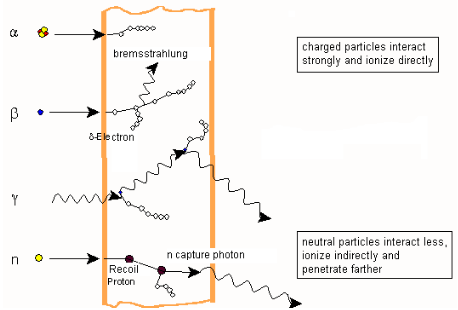
TRANSPORT

Solve Boltzmann transport eqn (HZETRN)

Deterministic, not Monte Carlo

- Want quick answers
- Real time dose as function of position & time
- Both transport & nuclear physics must run fast
- $\rightarrow$ Applied nuclear physics

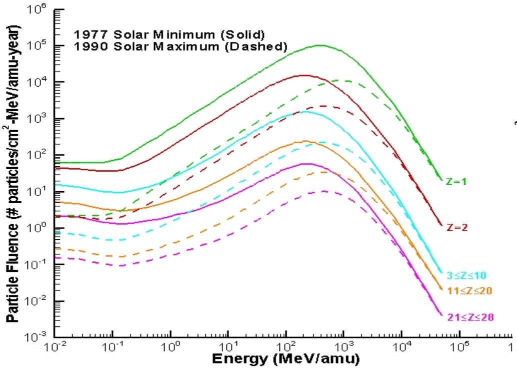


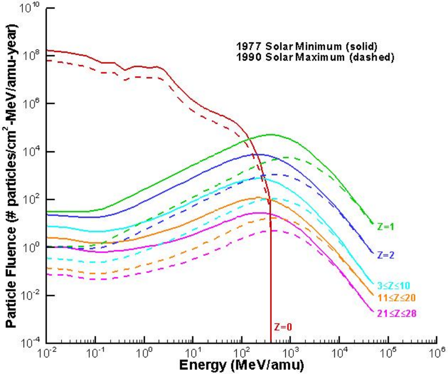


[Wilson et al., NASA-RP 1257, 1991]

[http://www.wikidoc.org/index.php/Ionizing_radiation]

Transport

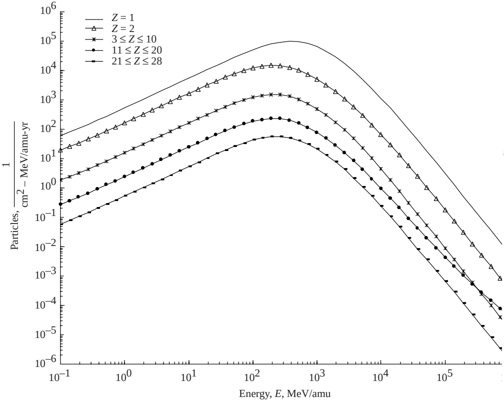


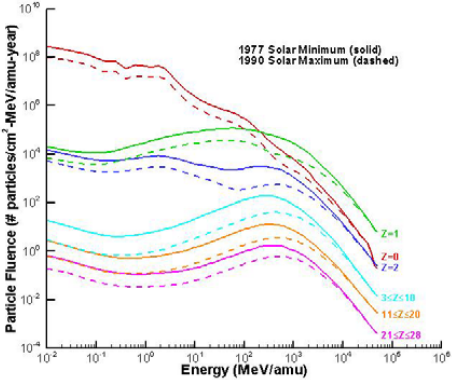


Free space GCR environment at 1AU

Lunar surface environment due to GCR

[Clowdsley et al., AIAA, 2006]

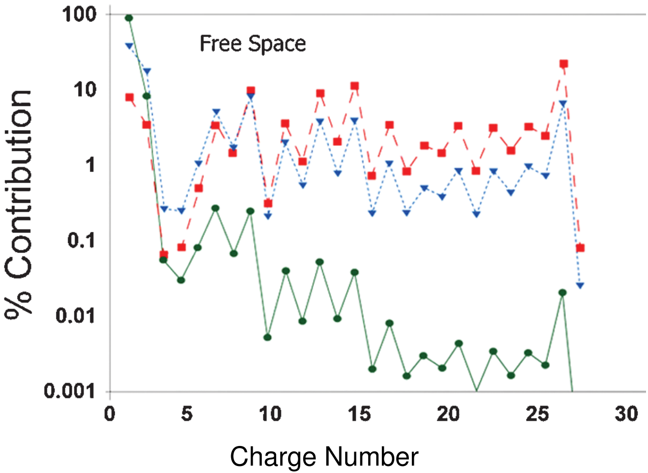




Left: Primary GCR spectra at Mars for 1977 solar minimum [Kim et al., NASA TP 208724, 1998]

Right: Martian surface environment due to GCR [Clowdsley et al., AIAA, 2006]

Applied Nuclear Physics Research



Relative contribution in fluence, dose and dose equivalent of different elements in the GCR spectrum. Calculation is an average over 1 year in solar minimum behind 5 g/cm^2 Al shielding.

[Durante & Cucinotta, Rev. Mod. Phys. 83, 1245, 2011]

Calculate cross sections

- Input to transport codes, which predict radiation environments
- Often need parameterizations

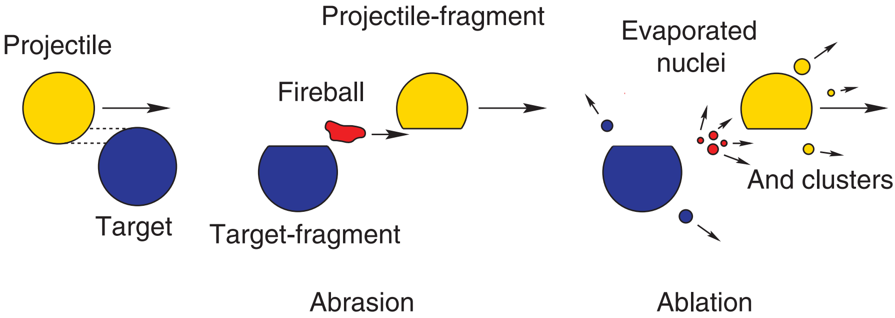
Electromagnetic dissociation

Nuclear fragmentation

- Heavy ions ($Z > 2$)
- Light ions ($Z \leq 2$) ^1H, ^2H, ^3H, ^3He, ^4He

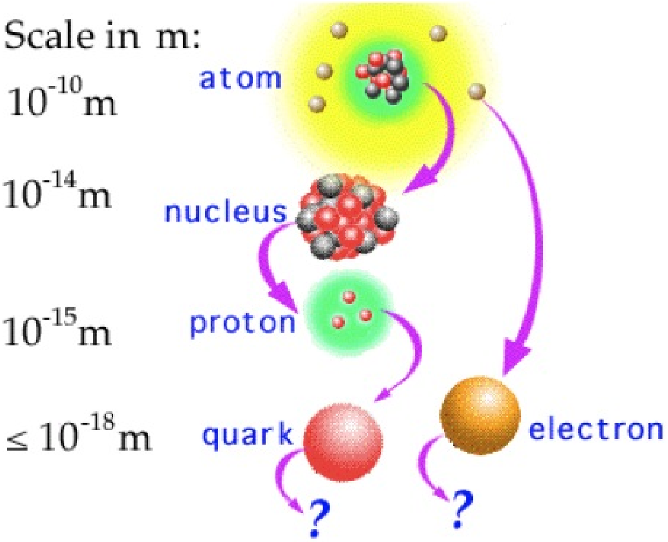
Hadron production & interaction

Neutron production & interaction



[Durante & Cucinotta, Rev. Mod. Phys. 83, 1245, 2011]

Hadrons / Pions



[http://www.learningwithatlas-portal.eu/en/node/93607]

HADRONS / PIONS

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

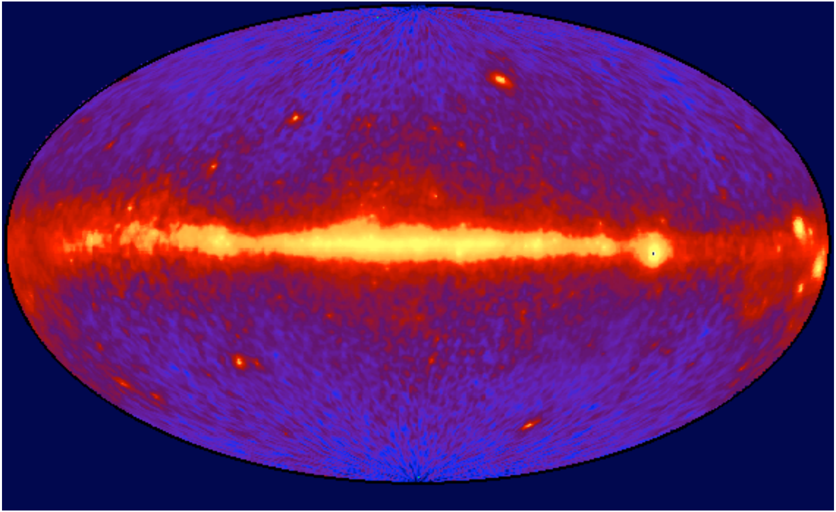
Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

[http://education.web.cern.ch, 2014]

Pions in the Sky

EGRET All-Sky Gamma Ray Survey above 100 MeV



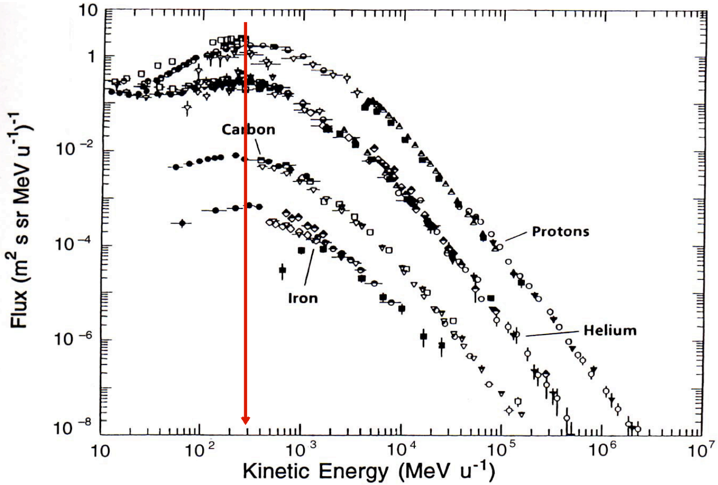
Emission from Galactic plane $p + p \rightarrow p + p + \pi^0 + \ldots \qquad \pi^0 \rightarrow \gamma + \gamma$

[http://heasarc.nasa.gov/docs/cgro/images/epo/gallery/skymaps/sky_egret.gif]

Maximum cosmic ray intensity
0.1 - 10 GeV

almost no data
1 - 10 GeV

Theory least understood
1 - 10 GeV



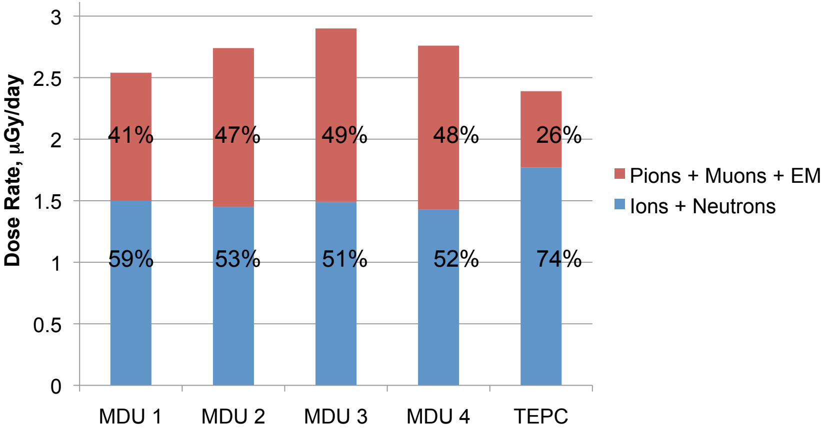
[Simpson, Ann. Rev. Nucl. Part. Sci. 33, 323, 1983]

PIONS MAKE LARGE CONTRIBUTIONS TO DOSE

[Slaba, Blattnig, Reddell, Bahadori, Norman, Badavi, Advances Space Research 52, 62, 2013]

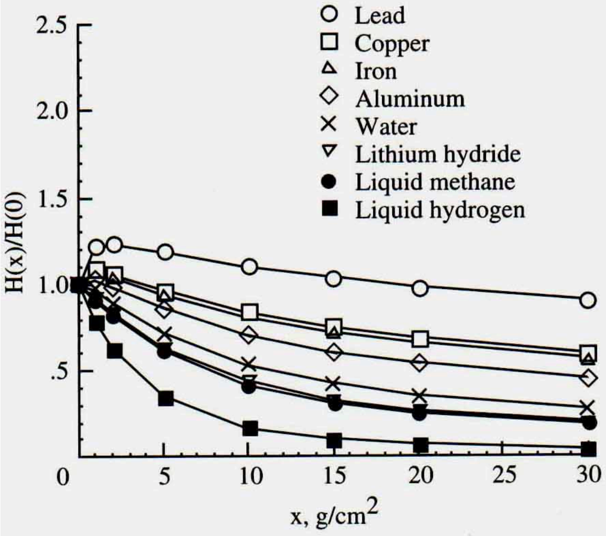
[Norman, Blattnig, De Angelis, Badavi, Norbury, Advances Space Research 50, 146, 2012]

[Aghara, Blattnig, Norbury, Singleterry, Nucl. Inst. Meth. B 267, 1115, 2009]



- Important discovery in space radiation

Transport - Materials compared to Aluminum



Dose Equivalent as a function of depth for various materials

[Wilson et al., Materials & Design 22, 541, 2001]

Transport

From radiation point of view, safest place is inside liquid hydrogen fuel tank!

Major result

- Low Z materials required for weight reduction necessary for future High Speed Civil Transport (HSCT) and for future spacecraft are *also* the best radiation protection materials
- Thank goodness!

MOON, MARS, JUPITER, SATURN

Moon

Short duration

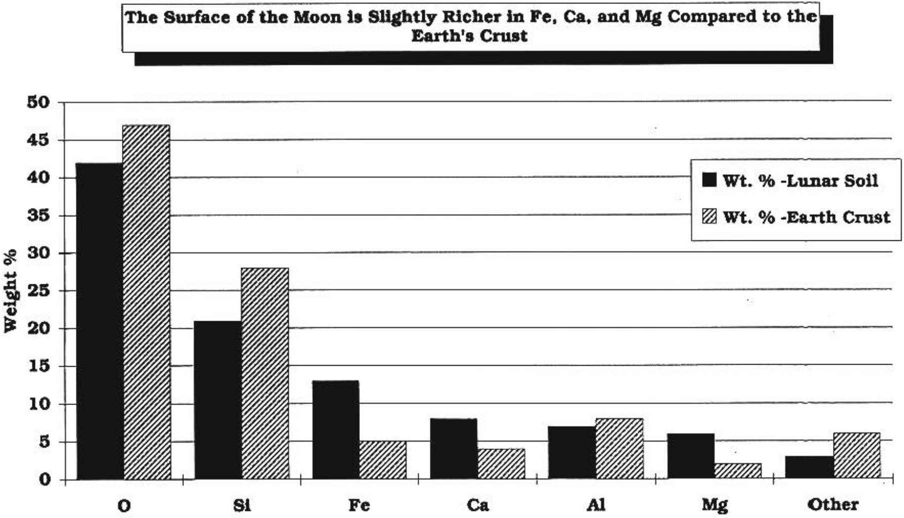
- Solar particle events

Long duration

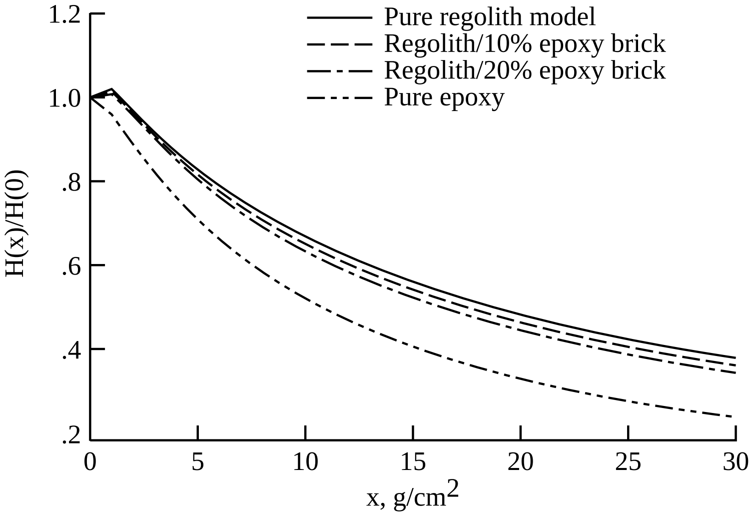
- Solar particle events
- Galactic cosmic rays

Lunar regolith composition

Material	Mass percentage
SiO_2	52.6%
FeO	19.8 %
Al_2O_3	17.6 %
MgO	10.0 %



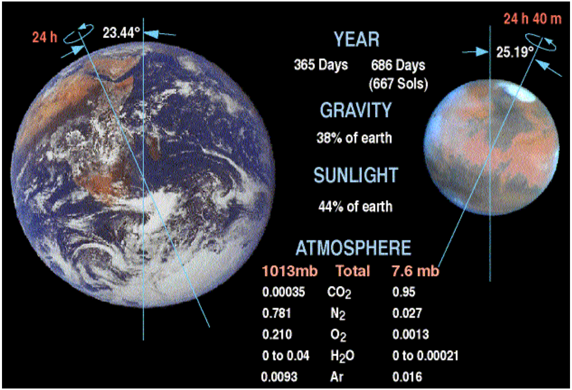
[http://fti.neep.wisc.edu/neep602/lecture12.html]



Attenuation of dose equivalent due to 1977 solar minimum GCR

[Simonsen et al., NASA Conference Publication 3360, 1997]

	Earth	Mars
Atmospheric thickness (g/cm^2)	1000	20
Magnetic field (Gauss)	1	0



[http://www-k12.atmos.washington.edu/k12/resources/]

Chemical composition of Martian atmosphere

Component	Percentage (%)
CO_2	95.32
N_2	02.70
Ar	01.60
O_2	00.13
CO	00.08

[De Angelis et al., Radiation Measurements 41, 1097, 2006]

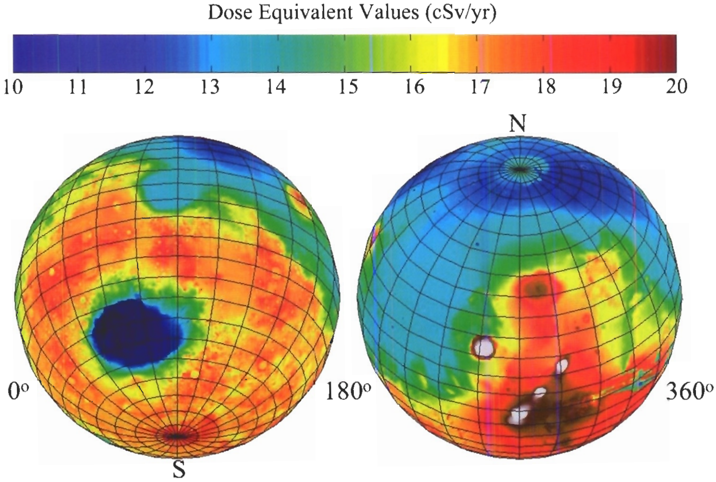
Chemical composition of Martian surface

Component	Percentage (%)
SiO_2	44.2
Fe_2O_3	16.8
Al_2O_3	08.8
CaO	06.6
MgO	06.2
SO_3	05.5
Na_2O	02.5
TiO_2	01.0

[De Angelis et al., Radiation Measurements 41, 1097, 2006]

GCR Environment

20 cSv/year = 200 mSv/year



Model prediction of dose equivalent from GCR. Calculations are shown at average skin depth near solar maximum. [Cucinotta, Radiation Research 43, S35, 2002]

Curiosity MSL RAD [Zeitlin et al. Science vol. 340, p.1080, 2013]:

Mars transit inside vehicle: 1.84 ± 0.33 mSv / day

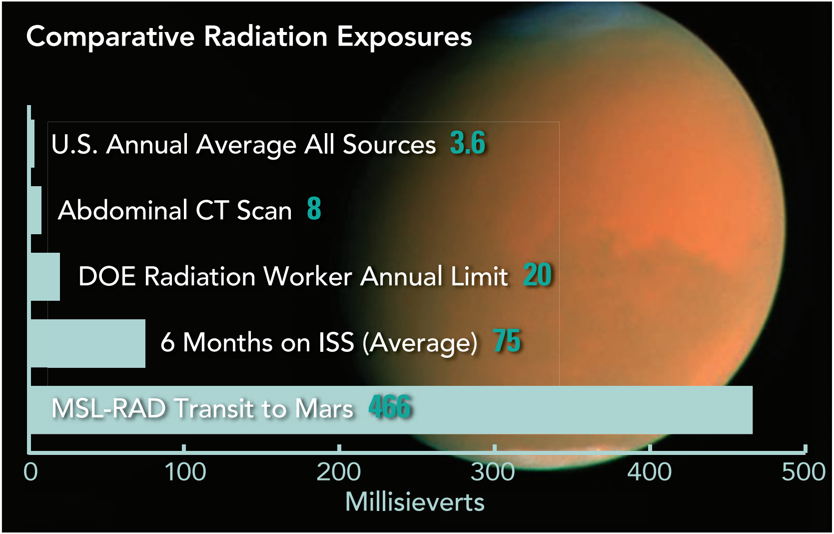
$\Rightarrow$ MSL (one way) 253 days gives 466 mSv

$\Rightarrow$ 331 mSv for 180 day cruise DRM

$\Rightarrow$ 662 mSv return trip

- Plus surface exposure 200 mSv ?
- Approaching and exceeding limits

Mars



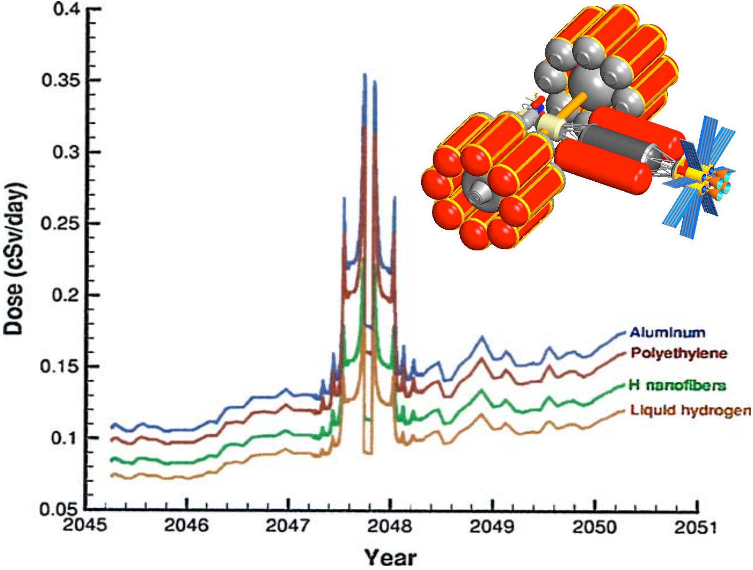
[Kerr, Science 340, 1031, 2013]

JUPITER

Intense radiation

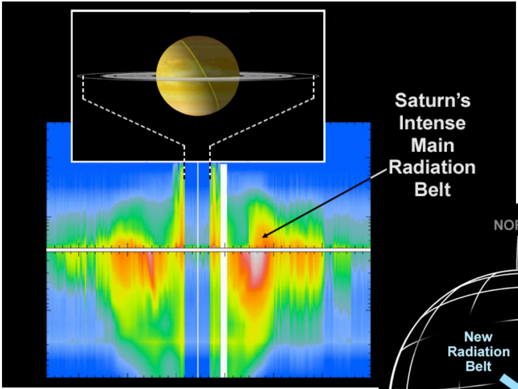
- On Io humans could not survive for more than a few hours
- Callisto

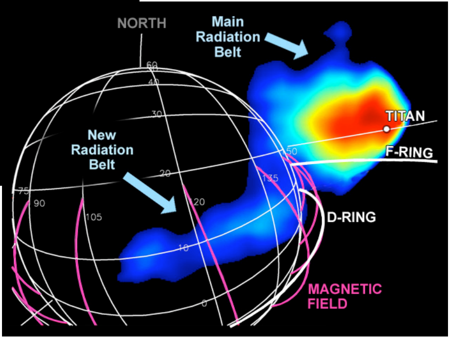
L1 TO CALLISTO SURFACE OPS (30 DAYS) & RETURN



[Wilson et al., Adv. Space Res. 34, 1281, 2004]

SATURN





[http://www.universetoday.com/15381/radiation-on-saturn/]

[http://www.nasa.gov/mission_pages/cassini/multimedia/pia06421.html]

CONCLUSIONS

- Further human exploration of solar system
- Radiation protection is a major issue
- Fundamental studies in nuclear physics, particle physics and biophysics still needed
- Many interesting research topics arise

THE END

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